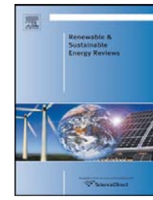
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Using modeling, satellite images and existing global datasets for rapid preliminary assessments of renewable energy resources: The case of Mali

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ABSTRACT

This paper presents a novel approach to the preliminary, low-cost, national-scale mapping of wind energy, solar energy and certain categories of bio-energy resources in developing countries, using Mali as an example. The methods applied make extensive use of satellite remote sensing and meteorological mesoscale modeling. The paper presents first results from applying the methodology in Mali and discusses the appropriateness of the results obtained. It is shown that northern Mali has considerable wind energy potential, while average wind speeds in the southern part are too low to make wind power a competitive option. Solar energy resources are shown to be abundant in all of Mali, though the highest values are found in the south. The temporal variation is relatively limited. Bio-energy resources are also concentrated in the south, but there are small pockets of high vegetation productivity in the irrigated areas of the Niger inland delta that might be interesting from a renewable energy resource perspective. Finally, the paper discusses the role that renewable energy resources might play in the energy systems of Mali, given the spatio-temporal distribution of renewable energy resources. It is argued that at the current price of about 70 US$/barrel for fossil fuels, renewable energy resources are becoming economically as well as environmentally attractive options.

Contents

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1. Introduction

This paper describes the objectives, methods and results of a study of the wind, solar and bio-energy resources of Mali [1]. The objectives are: (i) to demonstrate the feasibility of a method to produce preliminary assessments of the flow of renewable energy resources on a national scale using generally available satellite data, global data sets and model output; (ii) to take the first steps towards a comprehensive assessment and mapping of Mali's renewable energy resources; and (iii) to place this assessment in the context of Mali's current and projected future energy system. The focus is on three main categories of renewable energy resources: wind energy, solar radiation and the net primary productivity (NPP) of vegetation. The basic idea has been to create an overview on a national scale of the size and spatial distribution of the available resources. The approach taken has been to make use of satellite data (in the case of solar energy and NPP) and output from meteorological models (in the case of wind energy) to provide a first estimate of resources. Other renewable energy resources, such as hydro-power (presently satisfying as much as 80% of Mali's demand for electricity), have not been considered, since their assessment requires fundamentally different approaches.

The aim of this preliminary assessment of available renewable energy resources is to provide an input into the strategic long-term planning of Mali's energy system. Presently, the country's hydro-power resources, produced at relatively low cost, are being supplemented by electricity produced from imported fossil fuels. As the demand for electricity is expected to increase rapidly in Mali, a high rate of increase in power production is required. This may be based on increased use of the hydro-power resources, increased use of fossil fuels, or increased utilization of wind, solar or biomass energy. Hydro-power has a long 'lead time' and is associated with considerable social and environmental sustainability problems. Fossil fuels that are environmentally problematic are in a number of applications not as competitive as renewable energy solutions. In this context, it is claimed that a national-scale assessment of where and when renewable energy resources are available will be useful.

2. Methods and data

2.1. Wind energy mapping

The KAMM/WAsP method [2], a so-called numerical wind atlas methodology, can be used when more conventional methods, such as those used in the European Wind Atlas [3], are not possible due to a scarcity of high-quality, long-term measurement data. Although the results will not meet bankable accuracy requirements, they are valuable for energy planning purposes. In this method an approach called statistical–dynamical downscaling is used [4], applying the Karlsruhe Atmospheric Mesoscale Model (KAMM) described in [5,6].

In this application, because of Mali's large area, three overlapping calculation domains are used to cover the country. Covering the northern, central and southern regions, they measure 1170 × 720 km, 1320 × 795 km and 1380 × 840 km, respectively. The horizontal resolution used is 7.5 km. In this application the model domains extend in the vertical from terrain level to 5500 m above sea level, using 25 model levels.

Figs. 1 and 2 show terrain elevation and aerodynamic surface roughness length, respectively, for the three modeling domains used for this numerical wind atlas study. The surface elevation data are derived from NASA's Shuttle Radar Topography Mission (STRM30) dataset version 2. The dataset can be accessed via the USA's National Aeronautics and Space Administration (NASA) webpage (Internet link [1]). The roughness length data are derived from the United States Geological Survey (USGS) Global Land Cover Classification, also known as GLCC. The data can be accessed via a USGS webpage (Internet link [2]). The land-use types were converted to roughness lengths using a look-up table.

The large-scale atmospheric forcing required for the mesoscale modeling is obtained from the NCEP/NCAR reanalysis data-set on a

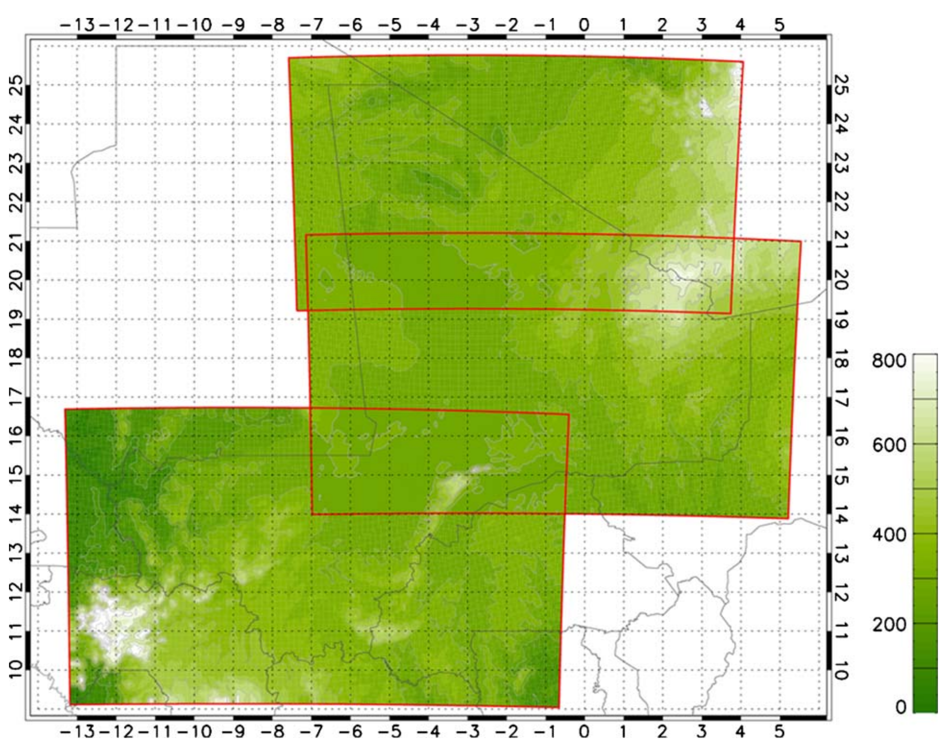


Fig. 1. The surface elevation over the three computational domains used for the KAMM mesoscale modeling at 7.5 km resolution for Northern Mali, Central Mali, and Southern Mali marked by the red rectangles. The contour interval is 100 m. The *x* and *y* axis are in longitude and latitude. The data is derived from NASA's Shuttle Radar Topography Mission (STRM) dataset version 2.

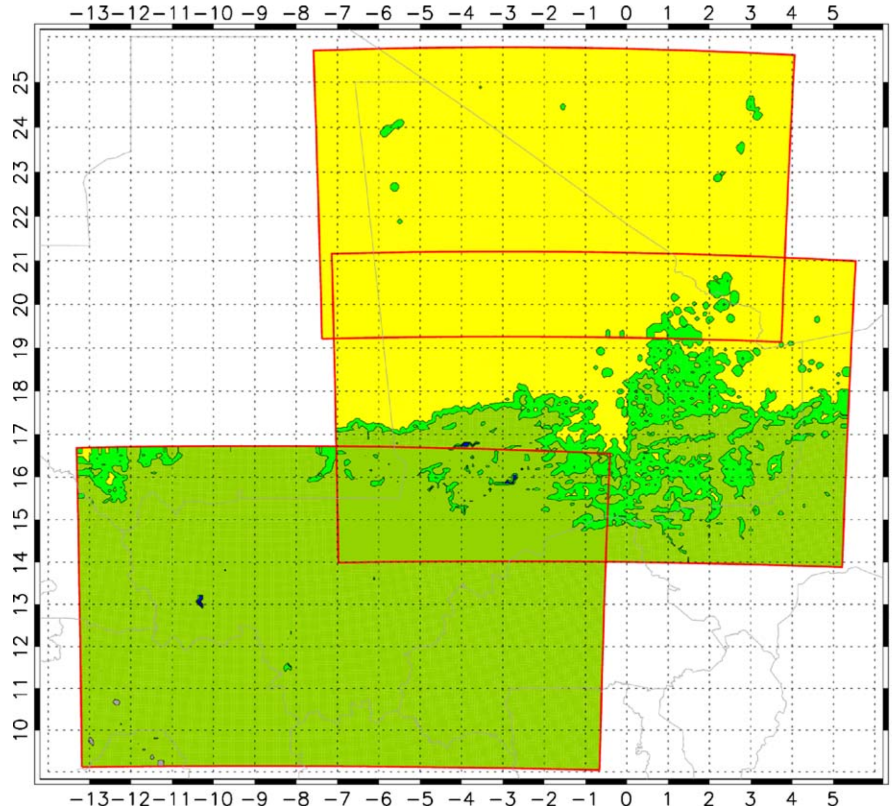


Fig. 2. The surface aerodynamic roughness length for the three modeling domains at a resolution of 7.5 km for Northern Mali, Central Mali, and Southern Mali marked by the red rectangles. The *x* and *y* axes use longitude and latitude as in Fig. 1. Colour key: Blue $z0 = 0.0002$ m, yellow $0.0002 < z0 < 0.002$ m, bright green $0.002 < z0 < 0.020$ m, green $0.020 < z0 < 0.2$ m, grey $0.2 < z0 < 0.60$ m. The roughness data is derived from the United States Geological Survey (USGS) Global Land Cover Classification.

longitude–latitude grid with a resolution of 2.5 × 2.5 degrees [7]. From this dataset a time-series of geostrophic wind and virtual potential temperature values for 0 m, 1500 m, 3000 m and 5500 m heights above sea level are derived using the years 1977–2006. The 30-year time-series data of wind and temperature profiles are used to determine three sets of wind classes, one set for each of the modeling domains. The wind classes represent large-scale climatology of wind speeds and atmospheric stabilities. The atmospheric stability is quantified using the inverse Froude number calculated between 0 m and 1500 m. Fig. 3 shows the wind classes for the Central Mali domain. The distribution of wind classes for the Southern Mali domain is similar, with slightly more weight on westerly wind classes. For the Northern Mali domain there is more weight on the north-easterly wind classes.

After the mesoscale simulations are complete, the results are compiled in the post-processing stage of the methodology. First, following the completion of the simulations, a weighted mean of the wind speeds at each mesoscale model grid point is calculated. The weightings for each wind class simulation are based on the wind class frequency of occurrence. This averaging operation yields a *simulated* resource map. Second, for each wind class simulation, the effects of elevation and roughness variation are removed with modules similar to those in the WAsP software [8], and then the weighted mean is calculated. This yields a wind atlas map, or a *generalized* wind map for flat surface condition of a specified roughness. Fig. 4 shows a schematic diagram of the wind class simulations and the post-processing steps.

2.2. Solar energy resource assessment

The estimation of global radiation by satellites is generally based on an estimation of the cloud cover, this being the main factor determining the reduction of the incoming solar radiation [9]. Images acquired by METEOSAT-8 are especially useful for this as the satellite performs a scan of the earth disk every 15 min, making it possible to monitor the temporal distribution of clouds

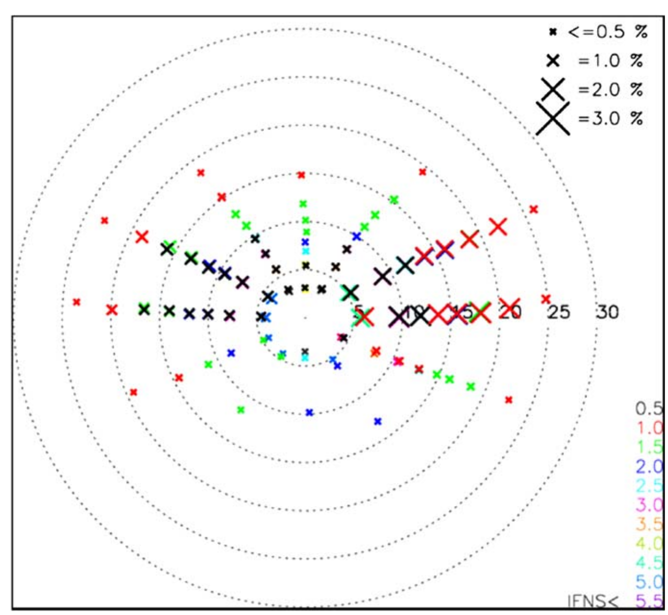


Fig. 3. The set of geostrophic wind classes for the Central Mali domain based on data for the period 1977–2006. Each cross represents a forcing wind speed (distance from the centre of the diagram) and direction. The speed scale is in m/s. The size of each cross represents the probability of the wind class. The frequency scale is given in the upper right hand corner. The colour scale indicating the inverse Froude number squared (IFNS) is given in the lower right hand corner.

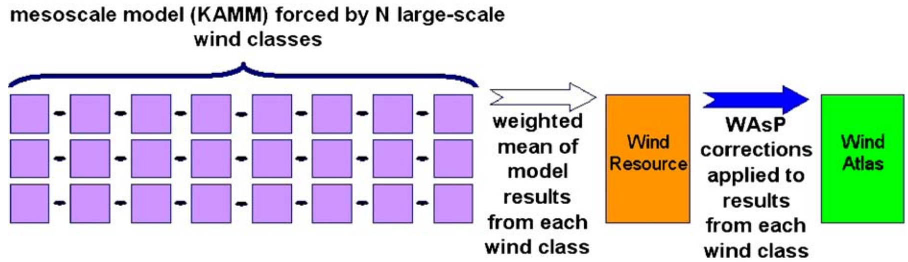


Fig. 4. A schematic diagram showing the KAMM/WAsP numerical wind atlas methodology. In this numerical wind atlas study, *N*, the number of wind classes is 136, 116, and 113, for the different calculation domains.

and thus solar radiation with high temporal resolution. The spatial resolution of the visible channels required for this monitoring is 3–5 km over West Africa. For Mali a consistent spatial resolution of 4 x 4 kilometers has been chosen.

The overall principle of the method used here for determining global radiation by means of geostationary satellite data is to combine information on the potentially available incoming solar radiation with information on the observed cloud cover. This includes an analysis of the temporal variation of the cloud distribution and radiative transfer modeling to estimate the incoming radiation on a daily basis. The applied method is based on a local adjustment of the work presented in Stisen et al. [10], which itself is largely based on the simple routine presented by Beyer et al. [11], with some modifications to the clear sky radiation model based on the work of Ineichen and Perez [12].

For the radiative transfer modeling, a single value for the Linke turbidity factor has been found from the SoDa webpage (Internet link [3]), where values are given as average monthly values. A single value has been applied to the entire area, the data being extracted for the central part of Mali.

From the more than 12,000 satellite images needed to cover the calendar year 2006, some gaps in available data were encountered. The periods with missing data have been filled by computing a simple average of the reflectance map from a similar time of day and period immediately before and after the time of the missing observations.

2.3. Mapping of bio-energy resources

The approach chosen involves the use of data on Net Primary Productivity (NPP), derived from time series of satellite images, in order to provide an overall picture of the spatial distribution of NPP. The objective is to provide a picture of where NPP is high enough, at the regional scale, to support its use for energy purposes. NPP represents the potentially available bio-energy resource flux, yet there are a number of competing alternative uses (and losses) of biomass for food, fodder and 'green manure', as well as fuel for burning, which implies that only a certain fraction of the NPP is available for energy purposes without imposing costs on other production systems and having negative consequences for environmental sustainability.

NPP is defined as the total photosynthetic gain of plant material (measured as dry weight or as the weight of carbon) minus respiratory losses per unit area and time (usually aggregated over a growing season). It includes both below- and above-ground plant material, but here we will restrict ourselves to the above-ground part.

In situ measurement of NPP is laborious, especially in heterogeneous landscapes, and the only viable option is to use time-series of satellite images to produce estimates of biomass production, and to calibrate and validate these using the available ground data. NPP estimation from satellite images has been performed for many years, and methods, algorithms and interpretations are well established in the literature. The basis for these techniques is the existence of a linear relationship between photosynthetic activity, the fraction of incoming radiation used by the plant cover to drive the photosynthesis and certain spectral reflectance properties of the vegetation cover, in particular the increase in reflectance between the visible/red and the near-infrared parts of the spectrum. This will be described in more detail below.

Estimation of NPP from satellite data functions particularly well in semi-arid areas, where the cloud cover is limited, allowing frequent data acquisition, and where the 'leaf area index' does not exceed a value of approximately 3. The requirement of daily coverage limits the possible choice of satellite/sensor-system. The standard source of data for NPP estimation for decades has been the AVHRR sensor onboard the NOAA satellite series. This sensor has provided reliable and consistent near-global data since 1982. AVHRR images have a spatial resolution of 1.1 km at nadir, and consistent data-sets are available with $8 \times 8\,\text{km}^2$ resolution. Today, the MODIS sensor onboard the AQUA and TERRA satellite systems provides an attractive alternative with a spatial resolution of 500 m for current purposes.

AVHRR and MODIS measure reflected solar radiation in the near-infrared and visible/red parts of the spectrum. From measurements in these two spectral bands, a 'vegetation index', which is a good proxy for photosynthetic activity on the ground, may be computed. The most widely used 'vegetation index' is the 'normalized difference vegetation index' or NDVI, calculated as

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - R}{\mathrm{NIR} - \mathrm{RED}}$$

NIR refers to the reflectance factor in the near-infrared, while RED refers to the reflectance factor in the red part of the spectrum.

In order to compute NPP from daily observations of NDVI, NDVI is first summed up for the entire length of the growing season, yielding the so-called integrated NDVI (iNDVI). Since the growing season depends on the type of vegetation in question, we have integrated over a full year. Subsequently, iNDVI may be used to estimate NPP, based on empirical relationships. Biome-specific relations have been established for use with MODIS data. Since we have no local data for calibration and validation, these standard relations are applied.

There are a number of reservations with respect to the accuracies which might be expected from this simple method of NPP estimation:

- Spectral properties of the soil background may cause a bias. This is obviously most important where the vegetation cover/leaf area index is low.
- There are significant differences in the iNDVI − NPP relationship between species, which are not taken into account in the biome-specific relationships.
- Given the coarse spatial resolution of the data, large variations in iNDVI (and thus in NPP) may exist within a pixel. This is

particularly important from a bio-energy point of view, where high productivity areas (e.g. irrigated fields) are interspersed with low productivity areas.

- NPP estimates are known to be biased in areas with high tree cover. This implies that the results should be interpreted cautiously, especially in southern Mali.
- Absolute NPP estimates may not be precise, though information on relative magnitudes and spatial distributions is reliable.

3. Results

3.1. Wind energy resources

Fig. 5 shows the annual mean *simulated* wind for Mali at 50 m above surface level. These maps give an overview impression of the variation of wind resources in space. However a word of warning, for any location on the map, one would not necessarily expect to have measured the same mean wind speed indicated by the map. This is because the map has been created using a surface description at 7.5 km resolution. In reality, the surface will be full of details in surface elevation and surface roughness. For example, small hills and forests, pertaining to elevation and surface roughness details, respectively, will not be resolved.

The annual mean wind speed at 50 m above surface level as it would be for flat terrain with a uniform roughness of 0.03 m was also calculated, i.e. when the local effects of resolved surface elevation and roughness change are removed.. This map is useful because it shows the mesoscale influence on wind resource, i.e. the variation of resource due to phenomena other than local orographic speed-up and roughness change. For reasons of limited space it is not shown in this article but can be found in [1].

Another powerful way to utilize the results of the numerical wind atlas is in the form of WAsP generalized wind climate files, which are generated by the KAMM/WAsP methodology. WAsP generalized wind climate files contain comprehensive information about the wind speed and direction distribution for various heights above ground level and for various surface roughness lengths. These files can be obtained for any location within the calculation domains on a grid with an approximate spacing of 0.1°. They can be applied using the WAsP software [8], where very high resolution terrain information can be used, to make estimates of annual energy production for specific turbines at specific sites.

The uncertainty of the preliminary results of the numerical wind atlas methodology is due to approximations and uncertainties involved in each step in the methodology. Contributors to the uncertainty may include:

- Description of the large-scale meteorological conditions from the NCEP/NCAR reanalysis. The global NCEP/NCAR reanalysis uses a rather coarse resolution, and its accuracy is better in regions of high density observations. In regions of scarcer measurement, the accuracy is degraded.
- Errors in wind velocities may lead directly to errors in wind resource.

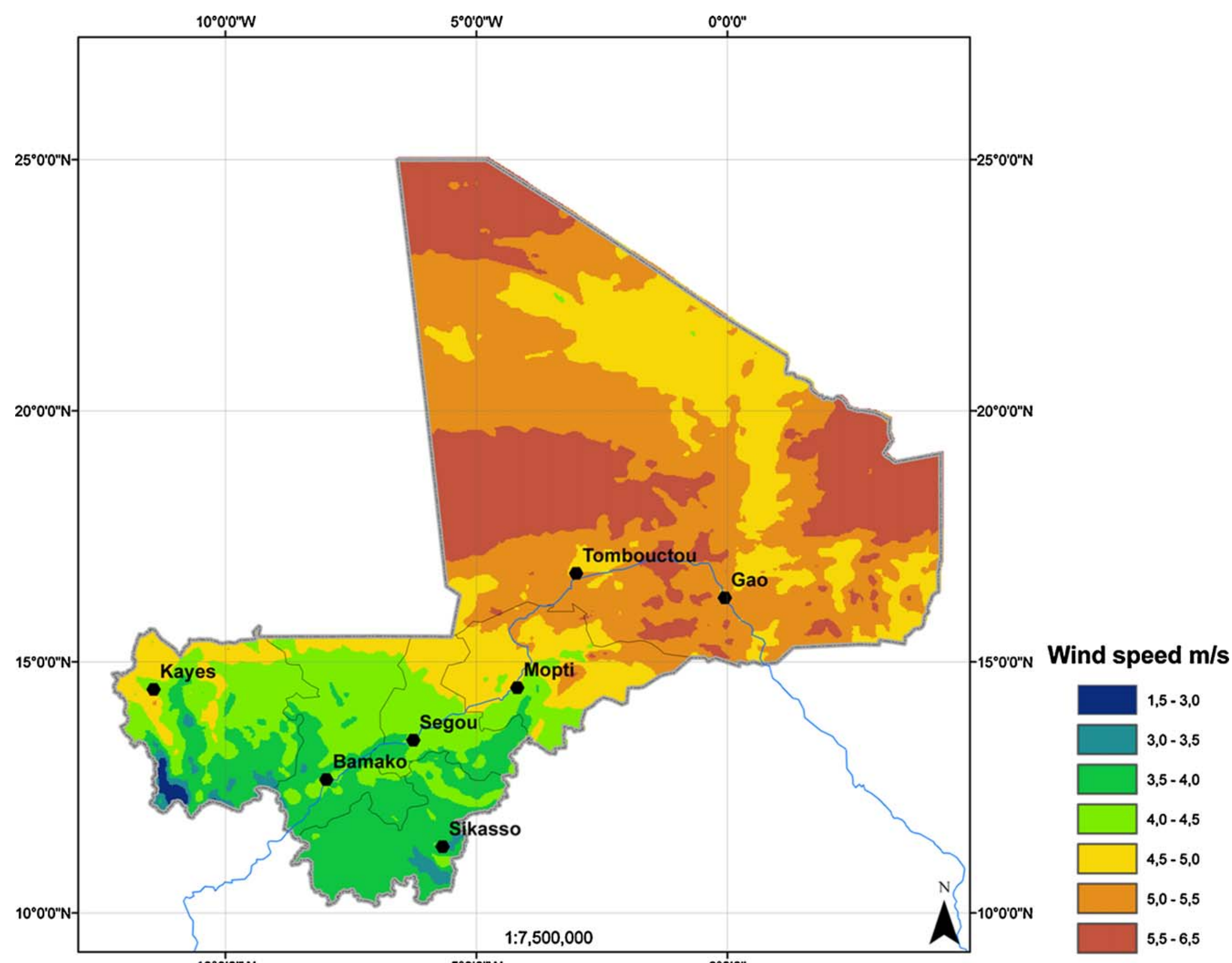


Fig. 5. Annual mean simulated wind speed at 50 m a.g.l. The contour interval is 0.5 m/s and colour scale is in m/s. Axes are given in longitude and latitude coordinates.

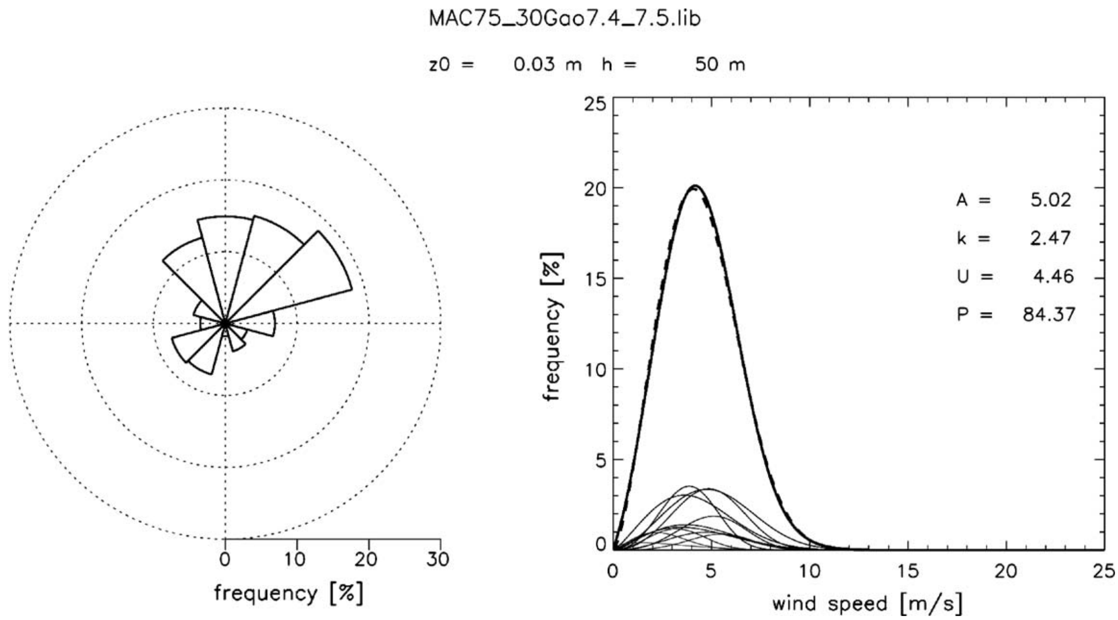


Fig. 6. The wind direction distribution and wind speed distribution given by the KAMM/WAsP numerical wind atlas for Gao, Mali.

- Errors in temperature profiles will lead to errors in stability and Froude number, and may give rise to spurious flow behavior in complex terrain.
- Determination of wind classes and their associated vertical profiles of geostrophic wind and temperature is a data-reduction process involving a certain loss of information.
- Description of the surface elevation is done on the basis of a digital elevation model with coarse spatial resolution. Serious consequences of errors in the orography include misrepresentation of high terrain and mountain passes. This may lead to incorrect interaction of flow with terrain.
- Errors in the estimation of the surface roughness may be caused by insufficient spatial resolution or by incorrect estimation of roughness length.
- The modeling set-up is limited in its ability to capture local diurnal thermally driven winds. Since KAMM modeling assumes a uniform and steady atmospheric forcing, any wind features due to transient and spatially varying forcings are not properly accounted for.

Previous numerical wind atlas studies using the KAMM/WAsP method and employing verification have demonstrated uncertainty of wind speeds at 50 m above ground level of between 5% and 15% [13,14]. The uncertainty of the model results in this case is expected to be between these levels of uncertainty, but it has not been verified by direct measurement, as would be the standard procedure.

The standard procedure for KAMM/WAsP results is to compare generalized wind climate statistics obtained from KAMM/WAsP and from WAsP analysis of measurement data at specific measurement locations. We refer to this as quantitative verification. When, as in this case, this is not possible, then a less satisfactory verification based on an inspection of summary wind direction and wind speed information is required. This we refer to as qualitative verification. To serve as a qualitative verification, the generalized wind climate at Gao produced by the KAMM/WAsP numerical wind atlas methodology shown in Fig. 6 is compared with the summary graphs for measurements made by GTZ in Gao shown in Fig. 7 [15].

It should be remembered that this comparison is only approximate because the measurement summary data include effects due to the local topography (orography and roughness) that are not included in the KAMM/WAsP result. This is why a WAsP analysis is required for a thorough verification. It should also be kept in mind that whereas the measurement data are given for 41 m a.g.l., the modeled data are given for 50 m a.g.l. What is more,

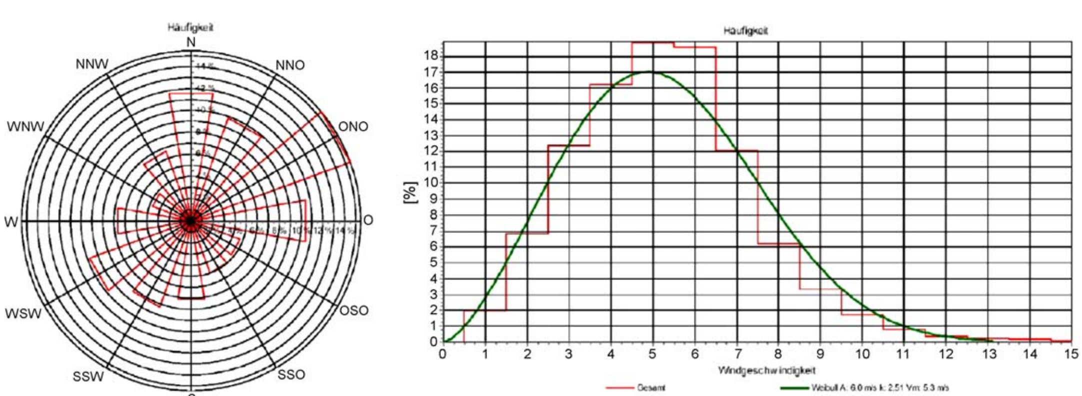


Fig. 7. The wind direction distribution and wind speed distribution given by measurements made by Deutsche Gesellschaft für Technische Zuzammenarbeit (GTZ) GmbH for the Gao measuring station reproduced from [15].

the measurement data only apply to two years of the measurement campaign, whereas the modeled data use large scale wind condition for a thirty-year period.

With all these caveats in mind, it can be seen that the modeled and observed wind direction distributions are in reasonable agreement. There are two principle wind directions: north-easterly and south-westerly. Both modeling and observations indicate that the north-easterly winds are more frequent than the south-westerly winds. Both modeling and observations indicate very few winds from either the north-west or the south-east.

Looking at the wind speed distribution for all wind directions, the modeling results suggest an annual mean of 4.46 m/s at 50 m a.g.l. for flat terrain with 3 cm roughness. The observations give an annual mean of 5.3 m/s at 41 m a.g.l., but for the actual terrain and the actual roughness. The wind speed is highly sensitive to the roughness and the orography, whereby a slight hill can lead to speed-up. Therefore we cannot conclude that the comparison between the modeling and the observed annual mean wind speed gives a disagreement. For example, if the roughness at the site is lower than 3 cm and/or the measurement mast is located on a slight hill, a WAsP analysis of the observed wind climate would lead to a generalized wind climate closer to the modeling results.

In summary, the wind resource has been estimated for all of Mali at 7.5 km resolution using the KAMM/WAsP numerical wind atlas methodology. Three domains were used to cover the entire country and three sets of wind classes used to represent the large-scale atmospheric forcings over the country. The final output includes maps of annual mean *simulated* wind and annual mean *generalized* wind, and the possibility of generating generalized climate statistics for any location in Mali, giving wind direction and wind speed distribution. First, qualitative comparison with wind measurements (Gao) indicates broad agreement of KAMM/WAsP and observations. In terms of the strategic planning of energy supply, it is evident from Figs. 5 and 6 that average winds are substantially greater in the north. If an average wind speed of 5 m/s is seen as the value below which wind power systems tend to become uneconomical, it is clear that large parts of southern Mali are not well suited to wind energy production, whereas northern Mali may be suitable in particular sites where local conditions enhance local flow further (such as hills and ridges).

In conclusion, the preliminary wind assessment provides an estimate that is expected to lie between 5 and 15% uncertainty. The assessment therefore provides a good first estimate of wind resources in Mali. The wind potential is interesting from an economic point of view, especially in the northern parts of the country. It is therefore strongly recommended that 4–6 wind measurement masts be set up to provide one year of measurements to be used for verification of the modeling results.

3.2. Solar energy resources

The output of the processing described above is maps covering Mali showing the actual spatial distribution of solar radiation at a specific time with a 15-min interval during 9.00–17.00 every day. These maps have been summarized to produce daily, monthly and yearly versions.

The yearly sum of all solar radiation is shown in Fig. 8 below. The values range from 1650 to 2000 kWh/m^2, with a general trend

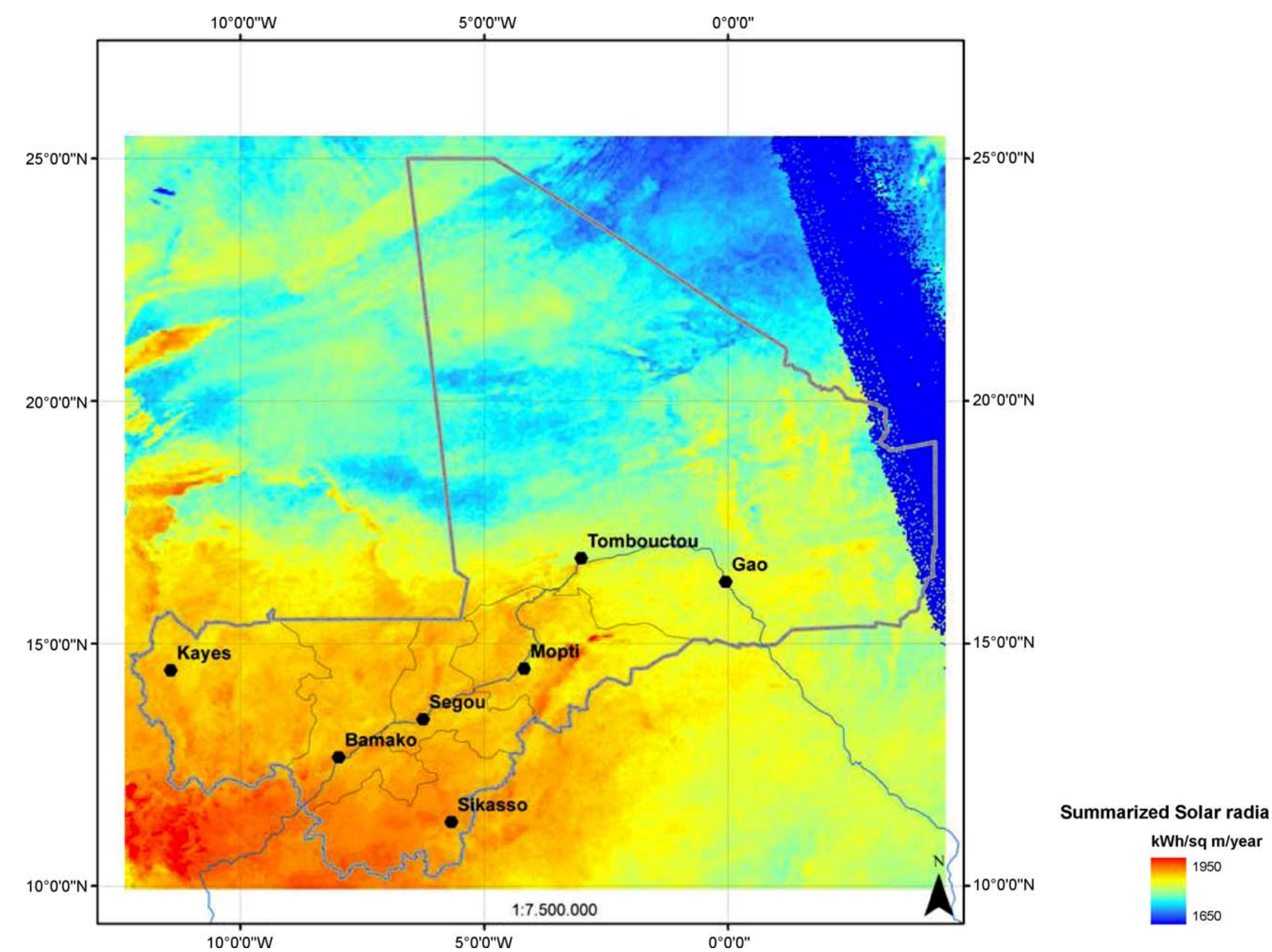


Fig. 8. The total solar radiation input for 2006.

towards larger values in the south and south-east of Mali and towards smaller values in the north and north-east.

As mentioned above, no ground measurements, which could have been used for validation purposes, were available [16]. Instead, a comparison of our results with data from the NASA dataset Surface meteorology and Solar Energy (SSE) (POWER/SSE Release 6.0) was made. This dataset has recently been updated so it now has global coverage of daily data on insolation incident on a horizontal surface (kWh/m^2/day) for the period 1983–2005. The data are available in tabular form on a daily basis or as monthly means for a specific area. The spatial resolution of the data is very coarse (1 × 1 degree), and the data themselves are based on the integration of a number of different data sources, including various satellite observations and ground-based measurements of several parameters. The comparison was performed on 3 different sites in Mali, respectively, in the north, centre and south (see Fig. 8 for locations), where daily data were extracted for a single 4 × 4 km pixel.

The data from the 3 different places reveal the inter-annual variation going from north to south, which is a function of both the position of the sun and the cloud cover. In the north, a more traditional 'bell shape' curve is found, with values ranging from approx. 4000 to 7000 Wh/m^2/day over the year. Going southwards, the annual variation in solar radiation becomes less pronounced, reaching an almost constant level of 5000–6000 Wh/m^2/day in the southern part of Mali. The daily variation is greater in the south due to varying cloud cover, especially in the period from May to September. The inter-annual variations are given in the monthly average plot shown in Fig. 9.

When comparing the result with the NASA data, it is also important to take the different nature of those data into account. The results reported here contain far more information on the

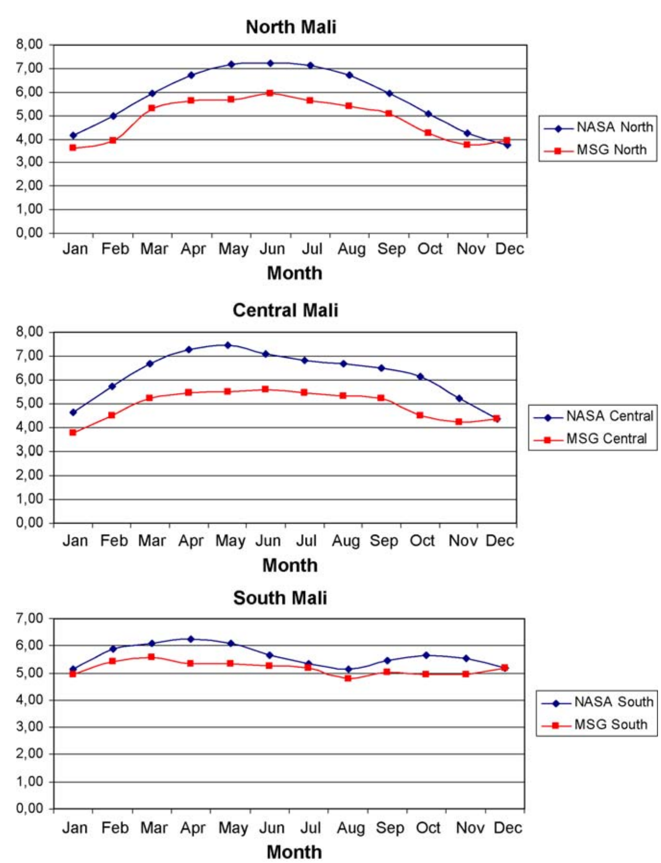


Fig. 9. Comparison between MSG derived radiation and NASA solar radiation data for the northern, central and southern part of Mali. Units are kWh/m^2/day.

spatial and temporal variability of the solar power potential than alternative data. Differences in absolute values between the current estimation and other data-sets are present and need to be resolved by more ground measurements. Such work is in progress.

The accumulated annual solar radiation input varies by less than 20% within Mali, with the highest values in the south, as shown in Fig. 8. The monthly accumulated values illustrated in map form in the project report show considerably greater variation (Internet link [4]). It is interesting to note that the radiation inputs in the north and south of Mali are out of phase, being highest in the south in October to April, and highest in the north in May to September.

3.3. Bio-energy resources

The NPP map for 2006, produced on the basis of MODIS data by means of the methods described above, is shown in Fig. 10.

For a set of land cover classes extracted from a land cover map produced on the basis of SPOT vegetation timeseries [17], average values and standard deviations of NPP for each class, as estimated using MODIS data for the year 2006, are given in Fig. 11. In Fig. 11, the 'irrigated croplands' class appears to have a surprisingly low average NPP. This may be due to the fact that the surface cover is extremely heterogeneous at sub-pixel scale, with very high NPP plots, e.g. rice fields, interspersed with barren ground and water. Seen from a bio-fuel perspective such areas might be quite interesting, in spite of the low average NPP, since the production is concentrated in small areas. This will allow the efficient and inexpensive harvesting of agricultural residues.

It may be concluded that the observed NPP is low for large parts of Mali. The figure given for the grassland class is lower than most other estimates, however, and we may ask whether the iNDVI-to-NPP conversion is giving rise to a general underestimation at the low end of the scale. Still, the most obvious conclusion from Figs. 11 and 12 is that only in the southernmost land cover classes does the average NPP exceed 1 ton of carbon per hectare (above ground). This will seriously limit the spatial domain in which there is a high potential for bio-energy production.

Another issue of importance when planning bio-energy production is the inter-annual temporal variability. The Sahel-Sudan zone is well-known for great rainfall variability, and basing a renewable energy system on biomass resources which are extremely variable in amount from year to year is obviously irrational. In Fig. 12, the temporal variability of iNDVI for four points in Mali is shown. The temporal variation has been derived from a study based on NOAA AVHRR data taken from the Global Inventory Modeling and Mapping Studies (GIMMS) (see also internet link [5]) with a (degraded) spatial resolution of around 8 × 8 km^2. The figures are therefore not directly comparable to the iNDVI values from the MODIS analysis.

It is clear from Fig. 12 that both the absolute and relative sizes of the variability are greatest the furthest north one goes, in Mopti. The reason for the higher variability may be that the rainfall itself is more variable to the north, and that the NPP is also more sensitive to rainfall variations in the north. There is the further complication that part of the iNDVI signal in the north derives from irrigated fields, the area and greenness of which depend on the river discharge, which reflects rainfall conditions in the Fouta Djalon, the source area of the Niger River. Rainfall in the Fouta Djalon may differ substantially from local conditions.

Very little information is available at the national level on the fractions of NPP that are harvested, grazed or burnt. In the cropped area, the agricultural residues are potential sources of biomass for energy uses, and since grain/residue-ratios are known, these may be estimated from national production statistics. Annual grain production reached 3.4 and 3.9 mill. t/year in 2005 and 2008,

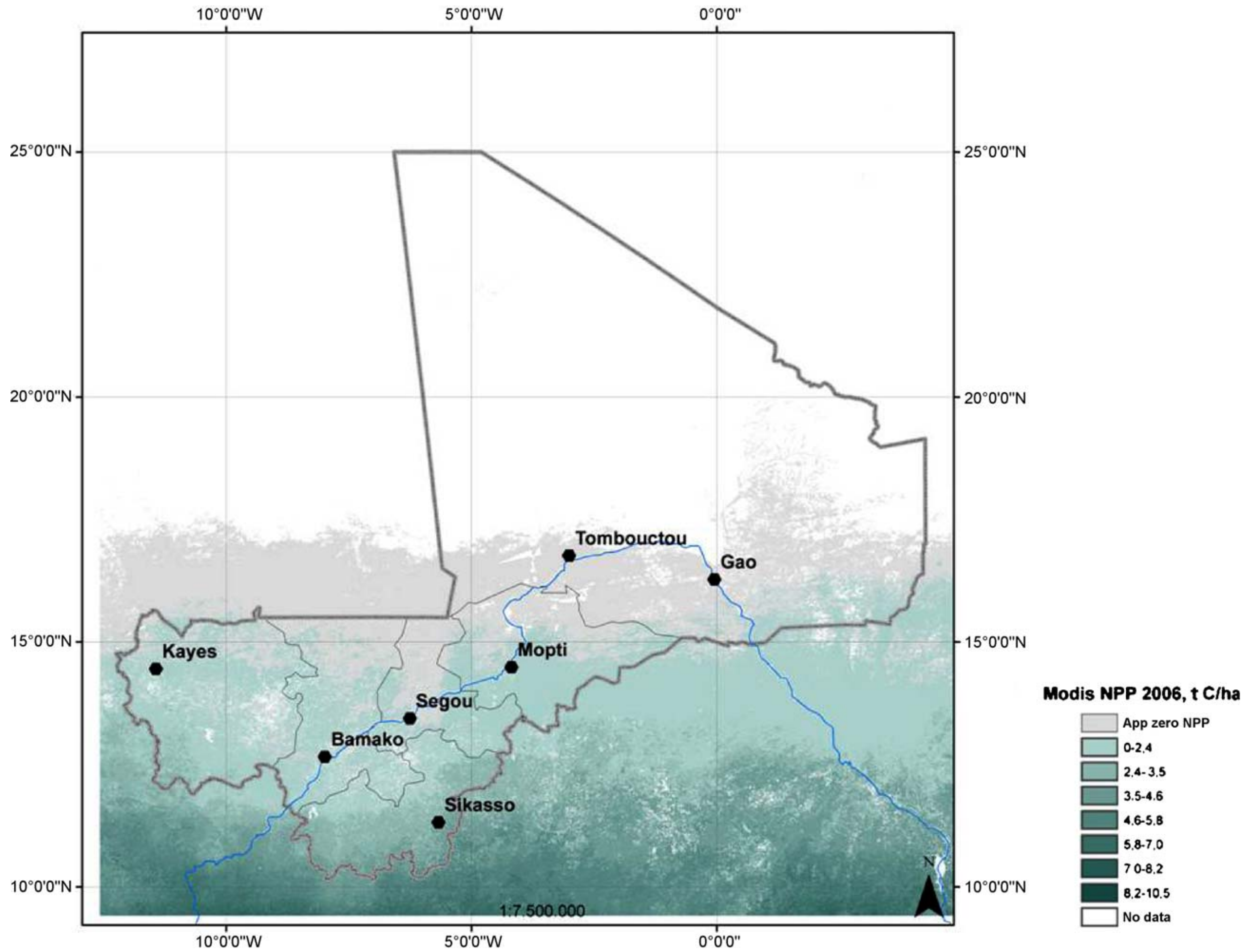


Fig. 10. MODIS NPP 2006.

respectively, while the straw-to-grain ratio varies between 1 and 2 between the most common crops, leading to a figure for straw production in the order of 5 mill. t/year (Internet link [6]). However, agricultural residues such as rice straw are used for other purposes and cannot be assumed to be available without imposing costs on other production systems, such as livestock production, or on the environment. In addition, inter-annual variations, e.g. due to rainfall, are substantial. If a high share of residues is used for cattle fodder, the absolute size of the remaining share will vary even more. Finally, agricultural residues need to be present in a certain spatial concentration to be economically exploitable. This implies that straw from irrigated rice cultivation may be the most economically attractive possibility.

The assessment of the flux of bio-energy resources presented above does not produce a 'resource map' in the sense of the maps of wind and solar energy resources. There are three reasons for this. First, the vegetation resources are not necessarily available for energy uses, since they have multiple other uses, such as human consumption and fodder for livestock. Some is burned and might potentially be available for energy uses if burning could be controlled. Secondly, since NPP may be modified, increased as well as reduced, by human action, bio-energy resources are not fixed in size like wind and solar energy resources. For example, land degradation caused by human over-use implies a reduction in NPP, while recent plans to increase irrigated rice production by 1.5 mill. t/year will cause a similar increase in the amount of straw available for fodder or energy uses. Thirdly, climate change, and in particular changes in rainfall, is likely to have a considerable impact on NPP, though the direction of any change in rainfall is at present quite uncertain [18].

It is clear from our data that the fraction of the biomass which is available for energy purposes with small negative impacts on other production systems and the environment is greatest in the far south, where a smaller fraction is likely to be consumed by livestock. Other areas where this available fraction is relatively high may be rice- and cotton-producing areas, where a substantial amount of residues are burnt, providing a potential resource for energy purposes. The fraction available is so far uncertain, but the *Centre National de l'Energie Solaire et des Energies Renouvelables* (CNESOLER) suggests that up to 135.000 tons of rice straw is currently burned in the zone of the Office du Niger [19].

The cultivation of crops specifically for energy uses is presently not very widespread in Mali, but high oil prices may cause this to

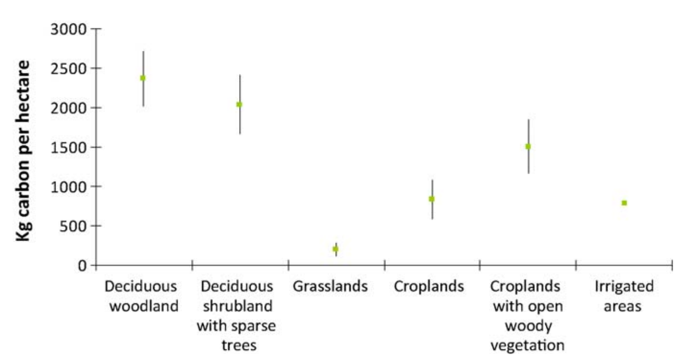


Fig. 11. Average values and deviations for MODIS NPP (in kg C/ha year) segmented by GLC2000 land cover classes. Note that deviations are given as the most common 25% of the results in a given land cover class.

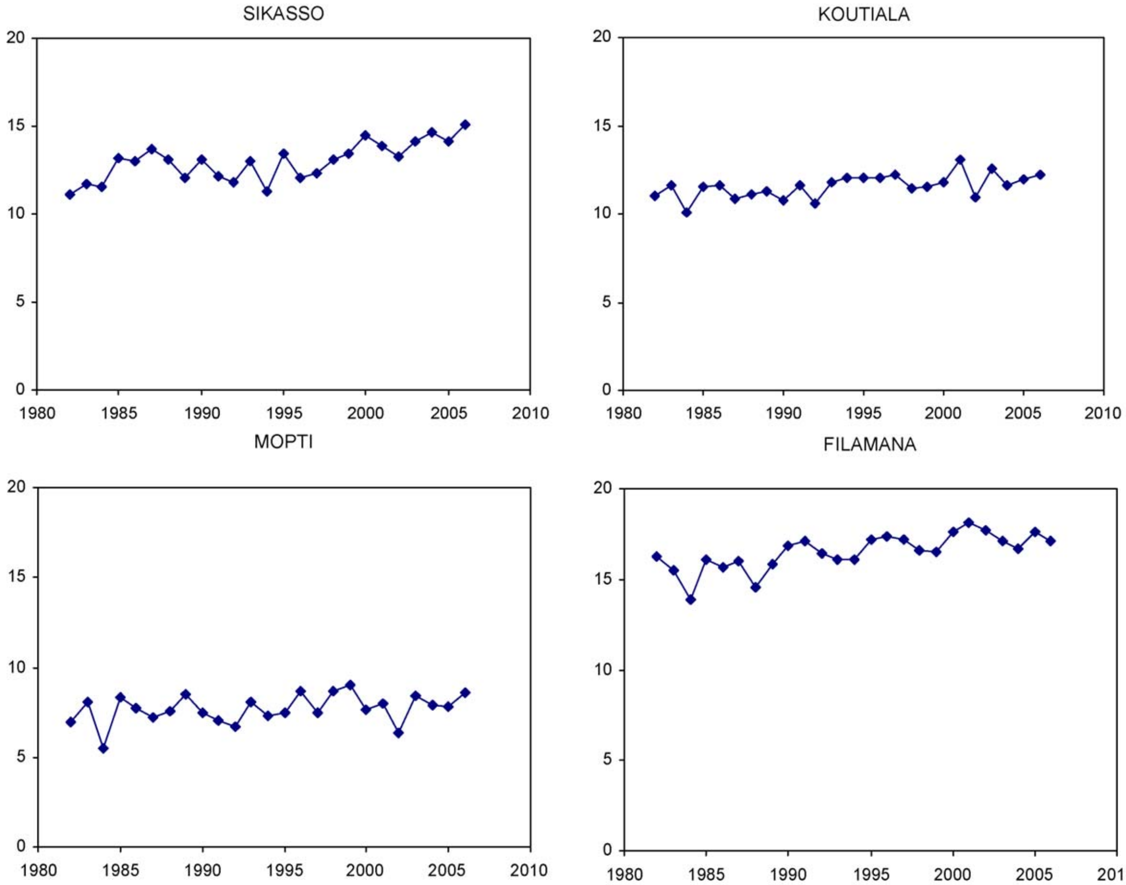


Fig. 12. Temporal variation of iNDVI for four areas in Mali for the period 1982–2007.

change rapidly. Our results say little about the potential, yet three pathways may be pointed out:

- Energy crops may be cultivated to feed into decentral power production.
- Plant oils produced by oil crops, such as *Jatropha carcus*, may be used to replace mineral oil or to provide a basis for bio-diesel production.
- Crops such as cassava and sugar cane may be cultivated as feed-stock for bio-ethanol production.

The realism of these pathways remains to be established, and many unresolved questions relating to their environmental, economic and social sustainability need to be addressed.

In the above, we have ignored the forestry sector, which currently contributes substantially to both rural and urban energy supplies in Mali. The NPP estimates include NPP in forests, yet different methods and data sources for assessing the production potential of Mali's forests are required. Such work is currently in progress.

Furthermore, it should be noted that the future of bio-energy production in Mali must be seen in the context of climate change mitigation under the Kyoto protocol. Replacement of fossil fuels by (more or less) CO_2-neutral renewable-energy sources may receive subsidies as part of the CDM system, and this may in principle make the expansion of bio-energy production (and wind and solar energy as well) more economically competitive.

4. The roles of renewable energy resources in Mali's energy system

In the preceding sections, the potentials for using wind, solar and bio-energy resources have been outlined and mapped. In the following, we will briefly summarize and discuss the findings and place them in the context of Mali's energy system.

4.1. The Malian energy context

The energy situation in Mali is characterized by a very low per capita consumption of energy. Only 14% of the population has access to electricity, and about 80% of gross energy demand is met by traditional biomass. In 2004 the installed production capacity of electricity in Mali was only 227 MW, including 153 MW of hydropower at Manantali (52% owned by Mali), Sélingué, Sotuba and Félou [20]. The national grid connects Bamako and thirteen main towns, mainly located in the south. In 2004 a further nineteen main towns were equipped with isolated grids supplied by diesel generators [21].

The national utility, *Energie de Mali* (EDM), was privatized in the year 2000, but after serious disagreements between the government and the concessionaires in 2005, the state reestablished its role as majority shareholder (66%). A rural electrification scheme based on private and cooperative ownership is managed by a government institution, *l'Agence Malienne pour le Développement de l'Energie Domestique et l'Electrification Rurale* (AMADER) and subsidized by a rural electrification fund. The scheme focuses on small-scale diesel generators for isolated grids, and on solar PV systems for village institutions.

In 2004 electricity was mainly produced by hydropower (81%). Electricity demand is increasing significantly, and according to the national energy plan from 2006, the maximum load is expected to increase from 124 MW in 2005 to 230 MW in 2010 and to 465 MW in 2020. According to the energy plan, this dramatic load increase is expected to be met through the establishment of new hydropower capacity, diesel generators and interconnections to neigh-

boring countries. The reality, however, is that there is a long lead time for establishing hydro-power due to environmental concerns, as well as difficulties in raising the capital for large-scale investments [22]. In line with a number of other African countries, Mali may therefore need to opt for a fair amount of diesel-based electricity, mostly in the isolated grids, but also in the coherent national grid.

At the same time, world market prices for oil have increased from an almost stable level of 20–30 US$ per barrel during a period of almost twenty years to the current level of 70 US$/barrel, yet with high variability and an expected strongly increasing long-term trend (Internet link [7]). It is evident that this will change the profitability of renewable energy relative to diesel-based solutions.

4.2. The potential role of wind energy

There have been a few attempts to establish wind power in Mali, but so far wind is only exploited in a few installations for water pumping. While the expansion of wind-diesel systems has been slower than anticipated for various reasons, [23–25], increasing oil prices and more reliable system designs have increased the feasibility of wind power in hybrid wind-diesel systems in recent years [see, e.g. 26–28].

Mali's wind energy resources are concentrated in the central and northern parts, from Mopti northwards, where average wind speeds of more than 5 m/s are found in large areas. Such wind speeds are generally considered to be the lower limit for the economically feasible exploitation of wind power as a supplement to diesel-driven systems. Since the northern and central parts of Mali are not connected to the national grid, a fair proportion of Mali's isolated grids are found here. There is hence a scope for supplementing diesel-driven systems with wind parks in the short term. This possibility is currently being explored. A feasibility study for supplying the town of Gao with a wind park of 1 MW, conducted in 2003, showed a reasonable level of feasibility, although financing is still being sought [29]. Another feasibility study for supplying the town of Timbouktou from a 1 MW wind park (4×275 kW), finalized in 2009, also documents that wind-diesel systems are competitive to pure diesel systems at this size [30].

In the longer term, wind power may contribute to the national grid, as hydro-power resources are unlikely to be able to fulfill the national demand for electricity.

4.3. The potential role of solar energy

Solar resources are already widely exploited in Mali, mainly as solar PV installations, but also as thermal applications used for water-heating, drying and cooking. The current exploitation is mainly the result of a long-term effort by various donors, the private sector and CNESOLER. According to information from CNESOLER, more than 800 solar pumps providing drinking water and more than 70,000 Solar Home Systems (SHS) had been installed in Mali by 2007. In addition, numerous installations have been made to provide electricity to village infrastructure such as dispensaries and schools, while more than 1000 kWp has been installed for telecommunication amplifiers and an unquantified but smaller number of solar water heaters, solar dryers and solar kitchens [31,32].

Exploitation of solar energy is expected to increase significantly in the years to come due to reduced panel prices and increasing oil prices. The price of equipment has decreased significantly since the beginning of the 1980s. Current system price estimates per Wp are 6000–10,000 FCFA (€9.3–15.7) for SHS and about 12,500 FCFA (€19.6) for water pumping [31], but further price reductions are expected due to greater competition and lower transaction costs as a result of an increasing Malian market, as well as to reduced production costs for imported solar panels as a result of a fast-growing global solar PV market [33].

Due to increased oil prices, it is predicted that under certain conditions hybrid PV–diesel systems may be more competitive than diesel systems in providing electricity in small isolated grids, as in the case of the newly established PV–diesel system in Kimparana, Mali [34,35]. Likewise, solar PV is expected to fulfil the need to provide electricity to village infrastructure such as water pumps, dispensaries, schools and administrative buildings in non-electrified villages and to provide electricity in terms of SHSs for people living in dispersed settlements and on the outskirts of electrified villages [36].

In contrast, large-scale grid-connected solar PV installations, as seen in OECD countries like Germany, Spain, Japan and the US, are not likely to be a least cost option in the near future.

4.4. The potential role of bio-energy

Besides the traditional use of fuel-wood from forestry, this study identifies agricultural residues as an interesting biomass resource for energy. While electricity has been produced from agro-industrial waste such as bagass and bran from rice, there have so far been only a few dispersed attempts to use agricultural residues for 'modern energy' in terms of briquettes for cooking [37]. The literature points at several examples of electricity being produced from the gasification or combustion of rice straw [38,39]. In Europe, and especially in Denmark, there is long experience of using straw and wood in thermal power plants in the range of 2–30 MW_{el} [40,41]. Based on this experience, the most probable contributions of bio-energy in the short term may be the use of agricultural and forestry residues for combustion to produce electricity in de-central power plants. The economic and environmental feasibility of such options should be explored further.

On the bio-fuel side, the ongoing production of plant oils from *Jatropha* may be an option on marginal land, and several ongoing projects are investigating this [42,43]. Preliminary findings also indicate bio-ethanol production from cassava as an interesting option which should be further investigated. Bio-ethanol from cassava is based on already operational 'first-generation technology', and cassava may well constitute an alternative to cotton as a cash crop [43].

5. Discussion and conclusions

Increasing oil prices have accentuated the focus on renewable energy, and it is acknowledged that a good estimation of available resources of renewable energy, such as wind, solar and biomass, is important for planning purposes in developing countries. In the search for rapid and cheaper assessments, this paper has described methods for resource assessment based on outputs from climate models, satellite images and existing global datasets for a rapid but preliminary assessment of renewable energy resources in Mali.

The study has focused on the assessment of wind energy, solar energy and bio-energy resources. The wind resources were estimated on the basis of model output, satellite data and existing global datasets, while the solar and bio-energy resources were estimated using satellite data. Maps were produced with a spatial resolution in the order of 5–10 km, depending on the data source. While wind and solar resources are relatively well-defined (though not necessarily easily estimated), bio-energy resources are conceptually far more complex to delimit. We have focused on the 'net primary productivity' (NPP) of the vegetation as the resource, yet the proportion of NPP that is actually available for energy purposes is difficult to assess because some NPP is harvested for human consumption and some is grazed by livestock.

The most obvious fraction to be used for energy purposes is the substantial fraction which is burnt at present. Additional ground measurements are needed to estimate current use and availability for energy purposes.

The preliminary wind resource map produced here shows potentially interesting wind resources in the north of Mali, while wind resources in most of the southern and more densely populated areas are generally poor. As regards solar energy resources, there is a high average solar radiation input and relatively small annual variations. The radiation is relatively evenly distributed spatially, but the intra-annual variations are greatest in the north. Bio-energy resources are found to be concentrated in the south, though small pockets of high productivity may be found further to the north in wetlands and irrigated areas along the Niger River.

The implications for Mali's energy system are complex and have not yet been fully explored. Wind energy seems to be a rational choice as a complement to diesel-driven electricity generation in the areas of northern Mali which are not connected to the national grid. Also, wind energy in terms of larger scale wind farms may supplement the inexpensive hydro-power that is presently supplying the major part of the electricity on Mali's national grid.

Solar PV installations benefitting from the relatively high solar radiation are already widespread in Mali. They provide electricity to village infrastructure such as dispensaries, schools and administrative buildings, as well as to people living in dispersed settlements and on the outskirts of electrified villages. Use of agricultural residues for combustion in thermal power plants may be a realistic option within the existing land-use patterns. Production of plant-oils for bio-diesel seems to be an interesting option on marginal lands. If oil prices rise, options for changed land use could be considered. Production of cassava as a cash crop for bio-ethanol, replacing current cash crops such as cotton, is an option which could be further examined. However, there are important environmental, economic and social sustainability issues that need to be examined in increasing the use of bio-energy resources.

In conclusion, this case study from Mali shows that it is possible to use mesoscale meteorological modeling, satellite images and existing global datasets to establish a preliminary mapping of renewable energy resources. Based on these experiences, this approach is recommended as a first step in future resource mapping projects as it offers valuable options for focusing the investigation in a second phase, thus providing more exact measures in selected areas.

Internet links

1. http://www2.jpl.nasa.gov/srtm/index.html (Accessed 21 December 2009).
2. http://edcsns17.cr.usgs.gov/glcc/ (Accessed 21 December 2009).
3. http://www.soda-is.com (Accessed 21 December 2009).
4. http://orbit.dtu.dk/getResource?recordId=233356&objectId=1&versionId=1 (Accessed 21 December 2009).
5. http://gimms.gsfc.nasa.gov/ (Accessed 21 December 2009).
6. http://countrystat.org/mli/cont/tablesuna/pageid/1._statistiques_nationales/a_production/fr (Accessed 21 December 2009).
7. http://tonto.eia.doe.gov/dnav/pet/hist/rbrted.htm (Accessed 21 December 2009).

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